



Enhancing Germination and Seedling Quality of Cashew (*Anacardium occidentale* L.): A Review on Propagation Media and Seed Pre-treatments

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Abstract— The production of high-quality seedlings is essential for improving the establishment, growth, and productivity of cashew (*Anacardium occidentale* L.). Seed germination and early seedling development are strongly influenced by propagation media and seed pre-treatment methods. Pre-treatments such as water soaking, mechanical scarification, and application of gibberellic acid (GA₃ at 50 - 200 ppm) significantly enhance germination rates from 65 - 70% in untreated seeds to 85 - 95%, while reducing mean germination time by 3 - 6 days. Propagation media enriched with organic components further improve seedling vigour; mixtures of soil, sand, and farmyard manure (1:1:1) increase seedling height, root length, and biomass by 20 - 30% compared to soil alone. Cocopeat-based media enhance moisture retention and root development, resulting in up to 25% higher root volume and improved lateral root growth. The integration of optimized media and effective pre-treatments produces synergistic benefits, including seedling survival rates exceeding 90% and more uniform growth in height, stem diameter, and leaf area. These approaches also improve physiological traits such as chlorophyll content and root-to-shoot ratio, which are critical for successful field establishment. Overall, the combined use of appropriate propagation media and seed pre-treatments enhances nursery efficiency, reduces seedling mortality, and supports sustainable cashew cultivation. Future research should focus on nutrient uptake efficiency and long-term field performance under different treatment combinations.



Keywords— Cashew, cocopeat, germination, propagation media, seed pre-treatments

INTRODUCTION

Cashew (*Anacardium occidentale* L.) is a perennial, tropical tree crop of high economic importance, cultivated primarily for its edible nuts and agro-industrial products. The successful establishment and long-term productivity of cashew orchards depend fundamentally on the production of vigorous, uniform seedlings in nursery

systems [1]. Inherent challenges in cashew propagation include variable germination rates, slow emergence, and uneven seedling growth, which can lead to high mortality rates and irregular field establishment. Improving germination performance and early seedling vigour requires an integrated approach combining effective seed pretreatments and optimized propagation media. Seed

priming has been widely studied as a strategy to enhance germination dynamics and seedling quality. Hydropriming (water soaking), chemical priming (e.g., urea, thio urea), and Osmo priming (e.g., potassium nitrate KNO_3) have been tested to improve seed performance. For example, priming with thio urea (5000 ppm) extended the storage life of cashew seeds and maintained >70 % germination after 13 months of storage, compared with poorer vigour in untreated seeds [2]. Chemo priming with KNO_3 (3 %) significantly increased seedling vigour index, seedling length, and the number of leaves in nursery raised rootstock seedlings [3]. In addition to chemical priming, hormonal treatments with growth regulators such as gibberellic acid (GA_3) enhance early growth traits (e.g., shoot length, leaf number) in cashew seedlings, though the optimal concentrations and timing require further refinement. Propagation media composition markedly influences water retention, aeration, nutrient availability, and root proliferation factors that are critical for uniform seedling development. Although many studies focus on simple mixtures of topsoil and sand, research indicates that substrates incorporating organic materials and finely balanced proportions of components often yield superior outcomes. In a comparative evaluation of growing media on cashew varieties, organic materials produced higher germination percentages (e.g., 93.2 %) and superior early growth parameters (height, stem diameter, leaf area) than sawdust or sawdust amended substrates, although the

interaction between variety and media also significantly affected growth [4]. Studies conducted in the Philippines further reveal that media containing garden soil, compost, and coco coir dust significantly increased seedling height, leaf number, and leaf area compared with other media combinations, highlighting the importance of organic carbon sources and physical texture in nursery substrates [5]. The interaction between optimized seed pretreatments and propagation media has profound effects on key nursery performance metrics. Enhanced germination percentages, accelerated emergence times, and higher vigour indices have been reported when seeds are primed and sown in carefully formulated substrates, often resulting in improved uniformity, root mass, and survival rates critical for field establishment. Although research in cashew lags behind staple crops, analogous studies in other perennial species affirm these benefits and support their application in cashew nursery protocols. Given the economic significance of cashew and the persistent constraints in nursery propagation, there is a compelling need to synthesize existing knowledge on seed enhancement methods and media development. A comprehensive understanding of how seed pretreatments and substrate composition interact to influence germination, early growth, and seedling quality is essential for establishing standardized nursery protocols that enhance propagation success and contribute to sustainable cashew production systems.



(A) Initial stage showing seed with emergence of radicle and cotyledons.
(B) Early seedling stage with elongation of hypocotyl and emergence of plumule.
(C) Development of young leaves in the nursery bag.
(D) Established nursery seedlings showing healthy vegetative growth.

Fig.1. Stages of seed germination and early seedling development in cashew

Role of Physical Properties of Media in Seedling Growth

The physical properties of propagation media particularly porosity, bulk density, and water holding capacity are fundamental determinants of seed germination, root development, and early seedling establishment. These properties control the availability of water, oxygen, and

physical space in the rhizosphere, which collectively regulate physiological processes such as root respiration, nutrient uptake, and cell elongation. Porosity and air-filled pore space govern the balance between water retention and gaseous exchange in the rooting zone. Total porosity refers to the proportion of pore volume (air + water) relative to media volume, and ideal propagation substrates often

exhibit total porosities exceeding 70 - 90% to support both moisture storage and aeration, far higher than mineral soils (35 % pore space) due to their lighter texture and engineered structure. Aeration porosity the fraction of pore space filled with air after free drainage is critical for oxygen diffusion to roots; values of 20 - 30% or higher are commonly recommended for vigorous seedling growth [6, 7]. A balanced pore distribution ensures that macropores ($>75\ \mu\text{m}$) provide pathways for oxygen and gas exchange, while micropores ($<30\ \mu\text{m}$) retain water accessible for uptake by the root system, thus supporting both respiration and hydration simultaneously. A total porosity within this range helps maintain oxygen concentrations above the critical threshold needed for root metabolic activity and new root formation (Caron & Michel, 2021)

Bulk density the mass of dry media per unit volume affects media compaction, root penetration, and mechanical resistance to growth. Lower bulk density is generally associated with higher total porosity and enhanced aeration, facilitating root elongation and lateral root proliferation. Fine, lightweight media such as peat and cocopeat often exhibit bulk densities between $0.12\text{--}0.25\ \text{g cm}^{-3}$, reflecting high pore space that encourages root exploration and water uptake (physical and chemical properties of soilless media). By contrast, more compacted or heavy media restrict root elongation and can reduce nutrient and water uptake efficiency, leading to reductions in germination success and early seedling growth by 15-25% or more compared with optimal media conditions in sensitive species.

Water holding capacity (WHC) is the volume of water retained in the medium after gravitational drainage and is strongly influenced by particle size distribution and organic content. Media containing high proportions of organic matter (e.g., peat moss, coir) exhibit greater WHC, sustaining soil moisture between irrigations without causing prolonged saturation, which can lead to hypoxia [6]. Ideally, WHC should complement porosity so that water remains available in the smaller pore fractions while large pores maintain aeration. Excessively high-water retention in fine textured media without sufficient macro porosity can impede oxygen diffusion and increase the risk of anaerobic stress, negatively affecting root respiration and seedling vigour. The interaction among these physical properties directly influences root zone processes: Oxygen availability: Adequate air-filled porosity ($>20\%$) ensures sufficient oxygen for aerobic respiration, which is vital for ATP generation and root growth; oxygen deficits reduce root elongation and nutrient uptake. Water dynamics: Balanced WHC supplies water for imbibition and metabolic processes without waterlogging, which can cause hypoxia and root decay. Mechanical resistance:

Lower bulk density and proper pore architecture reduce mechanical impedance, allowing roots to penetrate and expand effectively, enhancing overall seedling establishment. Raviv et al. [7] emphasized that media with a balanced air-filled porosity (20 - 30%) and adequate water holding fraction optimize root physiological activity and nutrient uptake, as roots require both water and oxygen in close proximity to sustain metabolic activities such as cell division and elongation. Conversely, poorly structured, compact media (high bulk density, low porosity) restricts root penetration, reduces oxygen diffusion, and can decrease germination efficiency by up to 20 - 25% relative to well aerated substrates in comparable plant systems. The physical properties of propagation media particularly porosity, bulk density, and water holding capacity shape the root zone environment and determine the success of seed germination and early seedling development. Optimizing these properties through appropriate component selection (e.g., peat, cocopeat, perlite, vermiculite) and mix formulation is essential for producing vigorous and uniform seedlings in nursery propagation systems.

Sand as an Aeration-Enhancing Component

Sand is primarily incorporated into propagation media to improve drainage and aeration. Its coarse texture reduces compaction and facilitates root penetration. Hartmann et al. [15] emphasized that sand improves oxygen availability in the root zone, which is crucial during germination. Kumar and Singh [8] observed that sand-amended media increased root length by 10 - 15% and improved root architecture. However, due to its low nutrient content and poor water retention, sand alone is insufficient to support seedling growth and must be combined with other components.

Soil as a Conventional Propagation Medium

Soil is one of the most widely used propagation media in nursery systems due to its natural nutrient content, microbial diversity, and ease of availability. It provides essential macro- and micronutrients, cation exchange capacity, and buffering potential, which support seed germination and early seedling growth. However, despite these advantages, sole soil as a propagation medium often exhibits significant physical and biological limitations that can restrict seedling performance. Compaction and low porosity in many mineral soils reduce aeration and impede root penetration, limiting oxygen diffusion to the root zone, which is critical for cellular respiration and elongation. Poor aeration, in combination with inconsistent water-holding capacity, can result in hypoxic stress, reduced root proliferation, and slower nutrient uptake [3]. Pathogen contamination is also more prevalent in

unsterilized or reused soils, increasing susceptibility to root rot and damping-off diseases, particularly in high-density nursery systems. Empirical studies have quantified these limitations. Seedlings grown in sole soil media often exhibit lower germination percentages (60 - 70%), reduced uniformity, and diminished vigour relative to organic-enriched or soilless media. Singh et al. [2] reported that cashew seedlings raised in soil-based media showed 18 - 25% lower biomass accumulation and shorter shoot lengths compared to those grown in mixed media containing soil, sand, and organic amendments. Reduced root length and lateral root development in soil-only substrates were attributed to mechanical impedance and suboptimal aeration, which limited water and nutrient absorption. Moreover, nutrient availability in soil can be inconsistent due to heterogeneity in texture, organic matter content, and mineral composition. In comparison, well-formulated mixed media allow controlled nutrient supply and enhanced moisture retention, promoting more uniform germination and seedling growth. These findings indicate that while soil contributes essential nutrients, its physical limitations and variable properties hinder optimal seedling development, highlighting the need for amendments or alternative substrates in modern nursery propagation [4].

Cocopeat as a Soilless Propagation Medium

Cocopeat, derived from the fibrous husk of coconut (*Cocos nucifera* L.), has emerged as a highly effective soilless propagation medium due to its favourable physical and hydrological properties. Its high water-holding capacity, approximately 8 - 10 times its dry weight, combined with high total porosity (85 - 95%) and low bulk density ($0.12 - 0.25 \text{ g cm}^{-3}$), creates an optimal environment for seed imbibition, root aeration, and uniform seedling growth [9]. The superior porosity of cocopeat ensures adequate oxygen diffusion to the root zone while simultaneously retaining sufficient moisture, minimizing the risk of drought stress or hypoxia. Experimental studies in cashew nursery systems have demonstrated significant improvements in germination and seedling development when using cocopeat-based media. Prasad et al. [9] reported that cocopeat-based substrates increased germination percentage to 85 - 90%, compared with 65 - 70% in conventional soil, and enhanced root biomass by 30 - 40%. Reddy et al. [17] further observed that cocopeat facilitated improved root proliferation, lateral root density, and seedling uniformity, leading to more robust seedlings suitable for transplantation. The light texture of cocopeat also reduces mechanical impedance, allowing easier root elongation and exploration, which is critical for early nutrient acquisition and growth. Despite its physical advantages, cocopeat is low in inherent nutrients, including nitrogen, phosphorus,

potassium, and essential micronutrients. Therefore, supplementation with balanced nutrient solutions or slow-release fertilizers is necessary to sustain long-term seedling growth and prevent deficiencies during nursery production. Additionally, because cocopeat is prone to compaction under repeated irrigation cycles, periodic loosening or mixing with coarse materials such as perlite or sand is recommended to maintain optimal aeration.

Vermiculite and Perlite in Media Optimization

Vermiculite and perlite are widely employed as amendments in propagation media to improve their physical and hydrological properties, thereby optimizing seedling growth and uniformity. Vermiculite, a hydrated phyllosilicate mineral, has a high cation exchange capacity (CEC) and large surface area, which enhances water retention and nutrient-holding capacity in soilless and mixed media. Perlite, a volcanic glass that expands upon heating, is chemically inert and highly porous, providing excellent aeration and drainage, reducing waterlogging, and preventing anaerobic stress in the root zone. Quantitative studies have demonstrated the benefits of these media components. Vermiculite incorporation can increase water retention of propagation substrates by 20 - 30%, whereas perlite can improve air-filled porosity and overall aeration by 15 - 25%, creating a balanced environment for root respiration and elongation [10]. Kumar et al. [11] reported that combining vermiculite and perlite in cashew nursery substrates increased germination rates by 15 - 20% and improved the seedling vigour index, including enhancements in shoot length, root length, and leaf area, compared to traditional soil or soil-sand media. Beyond physical improvements, the use of vermiculite and perlite also contributes to disease management. Improved drainage and aeration reduce the prevalence of root rot and damping-off pathogens by minimizing water stagnation in the root zone, thereby creating a less favourable environment for pathogen proliferation [12]. Additionally, vermiculite's nutrient retention capacity supports the sustained availability of macro- and micronutrients, which is particularly beneficial in nutrient-poor or soilless media. The synergistic use of vermiculite and perlite allows for the formulation of propagation media with optimal water-holding capacity, aeration, and nutrient balance, which is essential for achieving uniform germination, enhanced seedling vigour, and robust root development. Incorporating these materials is especially important in commercial nursery systems, where consistency and seedling quality are critical for successful field transplantation [10, 11].

Organic Amendments: Farmyard Manure and Vermicompost

Organic amendments are critical in optimizing propagation media by enhancing chemical, physical, and biological properties, which directly influence seedling growth and development. Farmyard manure (FYM) and vermicompost are widely used organic substrates that supply essential macronutrients (N, P, K), micronutrients, and organic matter, while also improving soil structure, water-holding capacity, and cation exchange capacity. In addition, these amendments support beneficial microbial populations, which facilitate nutrient mineralization, disease suppression, and root-microbe interactions, all of which contribute to improved seedling vigour [13, 14]. Vermicompost, produced through the decomposition of organic residues by earthworms, has been shown to significantly enhance seedling growth. Kumaresan et al. [13] reported that application of vermicompost increased total plant biomass by 20 - 35% compared with control media, attributed to enhanced nutrient availability, improved microbial activity, and the presence of growth-promoting substances such as humic acids, auxins, and cytokinins. These bioactive compounds stimulate cell division, root elongation, and overall plant vigour, making vermicompost a highly effective component in nursery substrates. Similarly, FYM incorporation into propagation media improves nutrient supply and soil physical properties. [14] observed that FYM-enriched media increased seedling height and leaf number by 25 - 30% and enhanced root proliferation due to improved substrate porosity and aeration. The gradual nutrient release from FYM ensures sustained availability throughout the early stages of seedling development, supporting uniform growth. In cashew nursery systems, the addition of organic amendments has been shown to improve the root-shoot ratio, enhance chlorophyll content, and increase overall seedling vigour, leading to higher survival rates during transplantation. The combined effects of improved nutrient availability, microbial activity, and optimized media structure facilitate the production of robust seedlings capable of rapid establishment in field conditions.

Composite Media and Synergistic Effects

Composite propagation media, which combine mineral and organic components such as soil, sand, and organic amendments, provide a balanced environment for seedling growth by integrating the advantages of individual components. Such mixtures optimize physical, chemical, and biological properties including aeration, moisture retention, and nutrient availability thereby supporting vigorous root and shoot development [15, 16]. A widely recommended formulation is soil: sand: FYM in a 1:1:1 ratio, which has been shown to produce superior seedlings

in various horticultural crops. The inclusion of sand improves drainage and prevents waterlogging, FYM supplies essential nutrients and enhances microbial activity, and soil provides structural support and baseline fertility. Singh et al. [2] observed that cashew seedlings grown in such composite media exhibited germination rates of 85 - 90%, with seedling height increases of 25 - 35% relative to soil-only media. Similarly, Reddy et al. [17] reported that cashew seedlings raised in composite media achieved maximum root lengths of 15 - 20 cm, shoot growth of 30 - 35 cm, and survival rates exceeding 90%, highlighting the synergistic benefits of combining physical, chemical, and biological enhancements in propagation substrates. The synergistic effects of composite media arise from the complementary roles of their components: enhanced aeration and drainage reduce root hypoxia, organic amendments supply nutrients and stimulate beneficial microbial activity, and a mineral base ensures structural stability. Collectively, these factors improve water and nutrient uptake efficiency, promote uniform seedling growth, and reduce susceptibility to abiotic and biotic stress during early development [10, 15].

Comparative Performance of Different Media

Comparative analyses of propagation media clearly demonstrate that individual components exhibit distinct advantages and limitations. Soil provides inherent fertility but often suffers from poor aeration and compaction, limiting root penetration and germination. Sand improves drainage and reduces waterlogging but lacks organic matter and nutrient supply. Cocopeat and other soilless substrates offer excellent physical properties, including high water-holding capacity, low bulk density, and superior porosity, but require external nutrient supplementation for sustained growth [9, 17]. Vermiculite and perlite improve moisture retention and aeration, whereas organic amendments such as FYM and vermicompost enhance nutrient availability and microbial activity [13]. Raviv and Lieth [10] concluded that optimized composite media, which integrate the advantages of multiple components, can improve seedling growth and vigour by 30 - 50% compared to single-component media. Empirical evidence from cashew nurseries confirms this, showing that carefully formulated mixtures achieve higher germination percentages, increased biomass, improved root-to-shoot ratios, and enhanced survival rates [2]. These findings underscore the importance of media integration, as a single component rarely provides the combination of physical, chemical, and biological properties required for optimal seedling development.



Fig.2. Common propagation media used for seedling production

Table 1. Common propagation media used for seedling production

Propagation Medium	Source / Composition	Key Properties	Role in Seedling Production	References
Soil (Topsoil)	Natural field soil	Moderate nutrient content, low porosity, high bulk density	Provides basic nutrients and anchorage	[10]
Sand	Weathered rock particles	High drainage, low WHC, high aeration	Improves aeration and drainage	[8, 15]
Cocopeat (Coir pith)	Coconut husk residue	High WHC (8–10×), high porosity (85–95%), low BD	Promotes root growth and uniform germination	[9]
Farmyard Manure (FYM)	Decomposed animal waste	Rich in organic matter, improves WHC and nutrients	Enhances fertility and microbial activity	[13]
Vermicompost	Earthworm-processed organic matter	High nutrient content, growth hormones, microbes	Improves seedling vigour and biomass	[16, 18]
Perlite	Expanded volcanic mineral	High aeration, low density, inert	Improves drainage and aeration	[10]
Vermiculite	Hydrated mineral	High WHC, moderate aeration, high CEC	Retains moisture and nutrients	[10]
Compost	Decomposed organic residues	Rich in nutrients, microbial activity	Improves fertility and biological properties	[14, 18]
Sawdust	Wood processing by-product	Low density, high aeration, low nutrients	Used as partial medium for aeration	[4]
Coco coir dust	Processed coconut fibre	High WHC, good aeration	Enhances seedling growth and root development	[5]

Seed pre-treatments

Seed pre-treatments are widely employed in cashew nurseries to enhance germination, improve seedling vigour, and ensure uniform plant establishment. Germination variability in cashew is often due to heterogeneity in seed maturity, moisture content,

physiological age, and the presence of physical or physiological dormancy [19]. Pre-sowing treatments stimulate metabolic activity, improve water uptake, and activate hydrolytic and antioxidant enzymes, thereby reducing mean germination time (MGT), improving

synchrony of emergence, and promoting early seedling growth.

1. Hydropriming (Water Soaking)

Hydropriming is a cost-effective pre-treatment involving soaking seeds in water for 12 - 24 h, enabling controlled imbibition without radicle protrusion. This process initiates early metabolic processes, including activation of α -amylase, proteases, and lipases, which catalyze the hydrolysis of starch, proteins, and lipids into soluble sugars and amino acids that serve as substrates for cellular respiration and biosynthesis [19]. Rapid cellular hydration during hydropriming restores turgor, facilitates cell division and elongation, and activates mitochondrial respiration, leading to enhanced ATP production and increased synthesis of nucleic acids and proteins. Cashew seeds treated with hydropriming show germination improvements from 65 - 70% to 80 - 85%, with reductions in MGT by 2 - 4 days, while also producing more uniform seedlings suitable for transplanting. Hydropriming also improves early root length (10 - 15 cm) and shoot elongation (20 - 25 cm), contributing to a higher seedling vigour index. Similar improvements have been reported in tomato, pepper, and okra, with 10–20% increases in germination and seedling vigour [19]. Optimization requires careful attention to soaking duration, water temperature, and seed physiological age, as excessive soaking may cause nutrient leaching or hypoxic stress.

2. Hormonal Treatments (Gibberellic Acid, GA₃)

Gibberellic acid (GA₃) is a plant growth-promoting phytohormone that accelerates germination and early seedling growth through multiple mechanisms. GA₃ stimulates embryo elongation, cell division, and expansion, activates α -amylase and other hydrolytic enzymes, and enhances protein synthesis, respiration, and metabolic activity in embryonic tissues [20]. In cashew, GA₃ applied at 50 - 150 ppm increases germination to 90 - 95% and reduces MGT by 3 - 6 days [21]. Seedlings treated with GA₃ also exhibit 20 - 30% increases in shoot length, 15 - 25% increases in root length, higher chlorophyll content, larger leaf area, and improved seedling vigour. GA₃-treated seedlings show better water-use efficiency, stress tolerance, and uniform establishment in the field [17]. GA₃ application is often combined with optimized propagation media, such as soil: sand: FYM (1:1:1) or cocopeat-amended substrates, producing synergistic effects on root and shoot growth, seedling biomass, and survival rates exceeding 90% [2].

3. Osmo priming and Nutrient Priming

Osmo priming involves soaking seeds in osmotic solutions (e.g., polyethylene glycol [PEG] 6000, KCl, or NaCl) to regulate water uptake, preventing overhydration while

activating metabolic pathways. This treatment enhances germination uniformity, synchronization, and stress tolerance, particularly under drought or salinity conditions, by increasing the activity of antioxidant enzymes (superoxide dismutase, catalase, peroxidase) and reducing reactive oxygen species [22]. Nutrient priming, using solutions of potassium nitrate (KNO₃), calcium, or micronutrients, supplies readily available nutrients during early germination, supporting radicle emergence, early root elongation, and shoot growth. In cashew, KNO₃-primed seeds germinate faster, with root lengths increased by 12–18% and higher vigour indices compared to unprimed seeds [2]. Osmo priming and nutrient priming can also improve seedling antioxidant capacity, photosynthetic efficiency, and resilience during transplantation.

4. Mechanical and Chemical Scarification

Scarification techniques aim to overcome physical dormancy by weakening the seed coat and improving water permeability. While cashew seeds generally exhibit low dormancy, mild mechanical or chemical scarification enhances water imbibition, reduces emergence variability, and accelerates early root and shoot elongation. Hartmann *et al.* [15] reported that scarification increased germination rates and uniformity in woody species. In cashew, seeds with thicker testa or partial coat imperfections respond particularly well, exhibiting 2 - 5% higher germination and improved initial root growth.

5. Organic and Biological Treatments

Organic pre-treatments, such as soaking seeds in cow dung slurry, compost extracts, or plant bio-extracts, supply nutrients, beneficial microorganisms, and bioactive compounds. [14] observed a 10–15% increase in germination and enhanced seedling vigour in cashew seedlings treated with organic slurries. These treatments also promote beneficial rhizosphere colonization, enhance nutrient cycling, and reduce pathogen incidence. Biological pre-treatments with plant growth-promoting rhizobacteria (PGPR) or arbuscular mycorrhizal fungi improve phosphorus and micronutrient uptake, stimulate root proliferation, and increase seedling biomass by 15 - 25%. Additionally, they enhance tolerance to abiotic stress during transplantation (23, 24). Integration of organic and microbial treatments with hydropriming or GA₃ has been shown to produce synergistic effects, yielding uniform, vigorous seedlings with superior field establishment potential.

6. Integrated Effects and Mechanistic Insights

The effectiveness of seed pre-treatments is maximized when combined with optimized propagation media. GA₃-treated seeds sown in composite media (soil: sand: FYM

1:1:1) achieve >90% germination, root lengths of 15 - 20 cm, shoot lengths of 30–35 cm, and survival rates exceeding 90% [2,17]. Hydro primed seeds in cocopeat or vermiculite-amended media show accelerated emergence, higher root proliferation, and increased vigour indices [9, 21]. These improvements result from synergistic interactions between seed metabolic activation and the physical, chemical, and biological properties of the media.

Well-aerated, nutrient-rich, and moisture-retentive media enhance water availability, oxygen diffusion, enzyme activity, reserve mobilization, and microbial interactions, allowing pre-treated seeds to germinate faster, develop stronger roots, and produce robust shoots. Collectively, these processes contribute to faster, synchronized germination, higher seedling uniformity, increased biomass, and improved field establishment [19, 21].

Table 2. Common seed pre-treatments and their effects on germination and seedling development

Pre-treatment Method	Treatment Details	Mechanism of Action	Effect on Germination (%)	Impact on Seedling Growth	References
Hydropriming	Water soaking (12 - 24 h)	Activates enzymes, improves water uptake	80 - 85%	Faster emergence, better root and shoot growth	[19]
Hormonal treatment (GA ₃)	50 - 150 ppm GA ₃	Stimulates enzyme activity, embryo growth	90 - 95%	Increased shoot length, leaf area, vigour	[17, 21]
Nutrient priming	KNO ₃ (2 - 3%) solution	Enhances nutrient availability and metabolism	80 - 88%	Improved root length and vigour index	[2]
Osmo priming	PEG / salt solutions	Regulates water uptake, induces stress tolerance	78 - 85%	Uniform germination, improved stress resistance	[22]
Scarification	Mechanical/chemical	Breaks seed coat, improves permeability	70 - 80%	Faster germination, slight growth improvement	[15]
Organic treatments	Cow dung slurry / compost extract	Supplies nutrients and beneficial microbes	75 - 85%	Enhanced vigour and microbial activity	[14]
Bio-inoculation	PGPR / mycorrhiza	Enhances nutrient uptake and root growth	80 - 90%	Increased biomass, stress tolerance	[24]
Thio-urea treatment	5000 ppm	Enhances enzyme activity and seed viability	75 - 85%	Improved germination and storage life	[2]

Integrated Effects of Seed Pre-treatments

The effectiveness of seed pre-treatments in cashew is strongly influenced by propagation media, environmental conditions, and seed physiological status. Research indicates that combining pre-sowing treatments with optimized propagation media produces synergistic effects, significantly enhancing germination, seedling vigour, uniformity, and survival [17]. For instance, cashew seeds treated with gibberellic acid (GA₃, 50 - 150 ppm) and sown in composite media composed of soil, sand, and organic amendments (1:1:1) achieved germination rates exceeding 90%, compared with 65 - 70% in untreated seeds grown in soil alone. These seedlings demonstrated enhanced root length (15 - 20 cm), shoot growth (30 -

35 cm), and biomass accumulation, as well as improved uniformity and survival rates >90% [2]. Similarly, hydro primed seeds sown in cocopeat or vermiculite-enriched media exhibited accelerated emergence, higher root proliferation, and increased vigour indices, underlining the importance of media pre-treatment interactions in nursery management [9, 21]. The synergistic benefits of combining seed pre-treatments with optimized media are attributed to the complementary effects on water availability, nutrient accessibility, oxygen diffusion, and microbial activity. Well-structured, aerated, and nutrient-rich media facilitate efficient enzymatic activity and mobilization of stored reserves, while pre-treated seeds respond more rapidly to favorable conditions. This results in faster germination, robust root systems, improved shoot growth, and uniform

seedlings suitable for transplantation under field conditions.

Physiological Mechanisms Underlying Seed Pre-treatments

Seed pre-treatments enhance germination and early seedling growth by modulating several interrelated physiological and biochemical processes. One of the primary mechanisms involves the activation of hydrolytic enzymes, such as α -amylase, proteases, and lipases, which catalyze the breakdown of stored starch, proteins, and lipids in the seed into soluble sugars and amino acids. These hydrolyzed metabolites provide essential energy and building blocks for embryonic cell division and elongation, thereby supporting radicle protrusion and early seedling establishment [19]. Another critical effect of pre-treatments is the improvement of cell membrane permeability and water uptake. Techniques such as hydropriming, Osmo priming, and scarification increase the fluidity of seed cell membranes, allowing faster and more uniform imbibition of water. This rapid hydration restores turgor pressure, reactivates metabolic pathways, and prevents desiccation stress during the initial stages of germination, ensuring that the embryo can resume growth efficiently [22]. Seed pre-treatments also enhance respiration and energy production. Pre-treated seeds demonstrate increased mitochondrial activity, leading to higher rates of ATP synthesis. This elevated energy supply supports the biosynthetic processes required for radicle

emergence and subsequent seedling growth, enabling seedlings to establish more rapidly under favorable conditions [20]. Furthermore, pre-treatments stimulate cell division and elongation. Hormonal applications, particularly gibberellic acid (GA_3), promote the elongation of embryonic cells, while growth regulators present in organic or microbial treatments further stimulate meristematic activity. This coordinated stimulation of cell proliferation and expansion contributes to faster root and shoot elongation, resulting in seedlings with improved structural integrity and vigour. Finally, pre-treatments facilitate the mobilization of stored reserves within the endosperm and cotyledons. Enhanced enzymatic activity ensures that nutrients and energy stored in the seed are rapidly converted into forms available for growth, supporting early seedling vigour and robust development. Collectively, these physiological mechanisms enable pre-treated seeds to germinate more rapidly, produce uniform seedlings, and develop stronger root and shoot systems. The effects are particularly pronounced when seeds are sown in well-structured, nutrient-rich, and aerated propagation media, which further optimize water availability, oxygen diffusion, and nutrient uptake. This integration of seed pre-treatment and media optimization results in seedlings with higher biomass, improved uniformity, and enhanced survival, ultimately strengthening field establishment and nursery performance [19].

Table 3. Physiological mechanisms underlying seed pre-treatments and their effects on germination and seedling development

Physiological Process	Mechanism Activated by Pre-treatment	Key Enzymes / Factors Involved	Effect on Germination	References
Enzyme activation	Pre-treatments stimulate hydrolytic enzyme synthesis	α -amylase, protease, lipase	Faster mobilization of stored reserves, early radicle emergence	[19]
Reserve mobilization	Breakdown of starch, proteins, and lipids into usable forms	Sugars, amino acids, fatty acids	Improved germination rate and uniformity	[19]
Water uptake (Imbibition)	Improved membrane permeability and hydration	Cell membrane proteins, aquaporins	Rapid and uniform germination	[22]
Respiration enhancement	Increased mitochondrial activity and ATP production	ATP, respiratory enzymes	Accelerated metabolic processes	[20]
Hormonal regulation	Increased synthesis/activity of growth hormones	Gibberellins (GA_3), auxins, cytokinins	Reduced dormancy, enhanced germination	[17]
Antioxidant activity	Enhanced ROS scavenging under stress	SOD, catalase, peroxidase	Protects cells from oxidative damage	[22]
Cell division & elongation	Activation of meristematic tissues	DNA, RNA, proteins	Faster radicle protrusion	[20]
Membrane repair	Restoration of membrane	Phospholipids,	Reduces leakage, improves	[19]

	integrity during imbibition	proteins	viability	
Nutrient uptake efficiency	Enhanced early nutrient absorption	Ion transporters, enzymes	Improved seedling establishment	[23]
Microbial interaction	Stimulation of beneficial rhizosphere microbes	PGPR, mycorrhiza	Indirect improvement in germination	[14]

CONCLUSION

This review highlights that combining optimized propagation media with seed pre-treatments significantly improves germination, seedling vigour, and survival in cashew (*Anacardium occidentale* L.). Organic-enriched media enhance root growth and nutrient availability, while treatments such as hydropriming and GA₃ promote faster and more uniform germination. The main advantages include improved nursery efficiency and higher-quality seedlings, though variability in seed quality and lack of standardized protocols remain limitations. These approaches have strong applications in nursery management and sustainable cashew cultivation. Further research should focus on standardization and long-term field performance.

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